

VU Research Portal

High-power frequency-stabilized laser for laser cooling of metastable helium at 389 nm

Koelemeij, J.C.J.; Hogervorst, W.; Vassen, W.

published in

Review of Scientific Instruments
2005

DOI (link to publisher)

[10.1063/1.1865752](https://doi.org/10.1063/1.1865752)

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Koelemeij, J. C. J., Hogervorst, W., & Vassen, W. (2005). High-power frequency-stabilized laser for laser cooling of metastable helium at 389 nm. *Review of Scientific Instruments*, 76(3), [033104].
<https://doi.org/10.1063/1.1865752>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

High-power frequency-stabilized laser for laser cooling of metastable helium at 389 nm

J. C. J. Koelemeij, W. Hogervorst, and W. Vassen^{a)}

Laser Centre Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

(Received 29 October 2004; accepted 25 December 2004; published online 22 February 2005)

A high-power, frequency-stabilized laser for cooling of metastable helium atoms using the $2\ ^3S_1 \rightarrow 3\ ^3P_2$ transition at 389 nm has been developed. The 389 nm light is generated by frequency doubling of a titanium:sapphire laser in an external enhancement cavity containing a lithium-triborate nonlinear crystal. With a maximum conversion efficiency of 75%, 1 W of useful 389 nm power is produced out of 2 W at 778 nm. While being stabilized to the $2\ ^3S_1 \rightarrow 3\ ^3P_2$ transition, the 389 nm frequency is tunable over ± 150 MHz with respect to the field-free atomic resonance frequency. This is accomplished by Zeeman tuning of the absorption lines used in the frequency-stabilization scheme. The setup for saturated absorption spectroscopy in an rf discharge cell, used to stabilize the 389 nm laser to the atomic transition, is described in detail. © 2005 American Institute of Physics. [DOI: 10.1063/1.1865752]

I. INTRODUCTION

In the past decade, laser cooling and trapping of metastable ($2\ ^3S_1$) helium (He^*) atoms has been the key to success in many cold-atom experiments. Examples of such experiments include Bose-Einstein condensation^{1,2} and photoassociation spectroscopy of metastable helium.³ Until recently, all magneto-optical traps of He^* employed the $2\ ^3S_1 \rightarrow 2\ ^3P_2$ transition at 1083 nm. Although laser cooling of He^* at 1083 nm on itself may be considered successful, it performs rather poorly as compared to laser cooling transitions in other atoms. Intrinsic limitations are the long wavelength (1083 nm photons carry relatively little momentum) and the small (1.6 MHz) natural linewidth, which does not allow for a large cycling rate.

An interesting alternative to laser cooling at 1083 nm is offered by the $2\ ^3S_1 \rightarrow 3\ ^3P_2$ transition at 389 nm. This transition involves photons with a 2.8 times larger momentum, whereas the linewidths of the two transitions are almost equal. The 389 nm laser-cooling force is therefore nearly three times larger than the 1083 nm laser-cooling force. A disadvantage is the $3.3\ \text{mW}/\text{cm}^2$ saturation intensity, which requires a relatively powerful laser source at 389 nm. In order to achieve efficient laser cooling and trapping in a 389 nm magneto-optical trap (MOT), a few-hundred mW of power at 389 nm is desirable. This can be obtained by second-harmonic generation (SHG) in an external enhancement cavity containing a nonlinear crystal, where a cw titanium:sapphire (Ti:S) laser provides the fundamental frequency.^{4,5} SHG in an external enhancement cavity forms the basis of the laser setup used in our laboratory (see Ref. 6 and references therein). The design and details of this setup will be discussed in the remainder of this article.

II. EXPERIMENTAL SETUP

A. Laser system for second-harmonic generation

The laser system is based on a Coherent 899-21 Ti:S ring laser, which is pumped by 10.0 W from a frequency-doubled Nd:YVO₄ laser at 532 nm (Millennia X, Spectra-Physics). The Ti:S produced maximally 2.1 W of single-mode narrow-band 778 nm light. The linearly polarized output of the Ti:S is sent through a perpendicular periscope to rotate the polarization by 90°, after which the horizontally polarized light is directed towards the enhancement cavity.

Figure 1 shows a schematic overview of the setup for frequency doubling. The waist of the Gaussian infrared beam is matched to the waist halfway between $M3$ and $M4$ of the TEM₀₀ mode of the ring cavity by the thin spherical lens L_1 (mode matching) to ensure optimum incoupling. The 778 nm light is coupled into the ring cavity through mirror $M3$, which has a specified reflectivity $R=99.0\%$ at 778 nm. Inside the cavity, a 10.5 mm long lithium-triborate (LBO) crystal, Brewster cut for 778 nm, is placed in the focus of the curved mirrors $M1$ and $M2$. These mirrors have a radius of curvature of 75 mm, which results in a minimum beam waist w_0 of 30 μm inside the LBO crystal. Mirror $M4$ (diameter 6 mm) is mounted on a piezo-ceramic tube and is controlled by a servo loop to stabilize the cavity length. The dispersive signal for the servo loop is obtained using the Hänsch-Couillaud scheme⁷ (see Fig. 1).

All cavity mirrors except the input coupler $M3$ have a coating which is highly reflective ($>99.9\%$) for the fundamental wavelength. The second-harmonic radiation is produced in the focus inside the LBO crystal, after which it leaves the crystal through the end face. Due to the orthogonal polarization (type I phase matching), the end face is not at Brewster's angle for the 389 nm beam, which results in 19.6% Fresnel losses. The second-harmonic beam is coupled out of the cavity through $M2$, which transmits 98% of the 389 nm light.

^{a)} Author to whom correspondence should be addressed; electronic mail: w.vassen@few.vu.nl

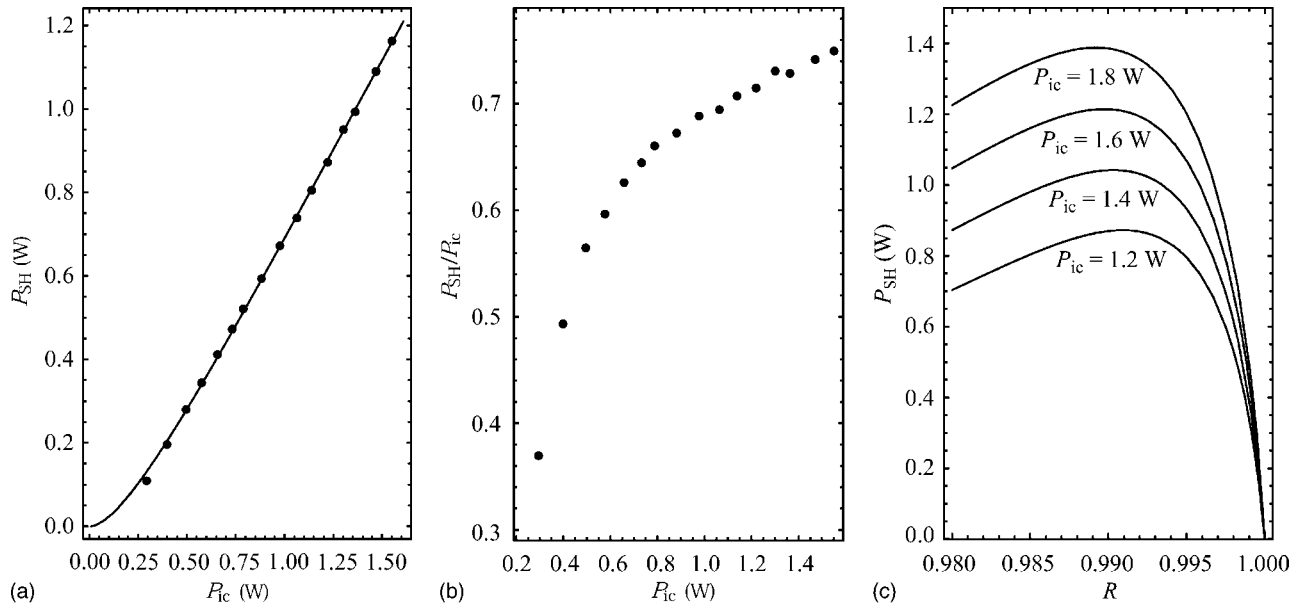


FIG. 2. (a) Dependence of the second-harmonic power P_{SH} at 389 nm on the fundamental power P_{ic} at 778 nm coupled into the cavity. The solid curve represents a fit to the data. (b) Net conversion efficiency P_{SH}/P_{ic} as a function of P_{ic} . (c) Calculated variation of the second harmonic power P_{SH} with the input coupler reflectivity R for various incoupled powers P_{ic} . The calculations were performed with $V_0 = 0.25\%$ and $\gamma = 5 \times 10^{-5} \text{ W}^{-1}$.

mized when the input coupler reflectivity R matches the effective round trip loss factor $1-V$, where V is the relative power loss per round trip. This can be seen from the expression for the enhancement factor $A = P_c/P_{in}$ (with P_{in} the fundamental power incident on the input coupler $M3$) for a perfectly mode-matched input beam¹¹

$$A = \frac{1-R}{(1-\sqrt{R(1-V)})^2}. \quad (2)$$

A part of P_{in} given by

$$K = \left(\frac{\sqrt{R} - \sqrt{1-V}}{1-\sqrt{R(1-V)}} \right)^2 \quad (3)$$

is reflected off $M3$. Indeed K vanishes when $1-V=R$, in which case the cavity is impedance matched. Apart from a round-trip loss factor V_0 , due to linear dissipation and scattering, V also includes losses due to second-harmonic conversion. Given Eq. (1), it can be shown that the relation between P_{SH} and P_{in} then becomes^{4,12,13}

$$\sqrt{P_{SH}} = \frac{4P_{in}(1-R)\sqrt{\gamma}}{[2-\sqrt{R(2-V_0-\sqrt{\gamma P_{SH}})}]^2}. \quad (4)$$

Solving the cubic equation (4) would in principle yield a relation between P_{in} and P_{SH} . This relation could be used for fitting data, like those shown in Fig. 2(a), to obtain information about γ and V_0 . Although Eq. (2) is derived assuming no power-dependent conversion losses, the expression suggests that $1-V$ may be replaced by $(1-V_0)(1-\gamma P_c)$ to account for conversion losses. Then, together with Eq. (1) a (nontrivial) relation between P_{in} and P_{SH} can be found using MATHEMATICA. Although the derivation for this expression is not rigorous, it reproduces the numerical results obtained with Eq. (4) to well within 0.1% for the entire range of realistic experimental values for P_{in} , γ , and V_0 .

The thus found relation between P_{in} and P_{SH} is used for fitting measured data shown in Fig. 2(a). Here, the values for P_{SH} have been corrected for the 98% transmission of $M2$ and the 19.6% Fresnel losses at the Brewster face of the LBO crystal (P_{SH} differs from the useful power, which is the SHG power transmitted through $M2$). Also, a relatively large fraction of P_{in} (typically 20% for powers between 0.5 and 2 W) is reflected off $M3$. For realistic cavity parameters, the fraction of noncoupled incident light due to impedance mismatch can be calculated using Eq. (3) [which has been modified to account for conversion losses similar as done for Eq. (2)] to be less than 2% for $P_{in} \geq 1$ W. It is therefore concluded that the noncoupled light is predominantly due to imperfect mode matching. To take this into account, in Fig. 2 P_{in} is replaced by the amount of light coupled in P_{ic} , which is defined as P_{in} minus the fundamental power reflected by $M3$. Obviously, this definition is only correct if the amount of light, reflected by $M3$ due to impedance mismatch, is negligible compared to the total amount of reflected light.

With the known value for R as input, the loss factor V_0 and the single-pass conversion efficiency γ are used as parameters to fit expression Eq. (2) [replacing $1-V$ by $(1-V_0)(1-\gamma P_c)$] to the data in Fig. 2(a). In this way $V_0 = 0.25\%$ and $\gamma = 5 \times 10^{-5} \text{ W}^{-1}$ are inferred. The fitted value for γ is in good agreement with the theoretical value, $\gamma = 4 \times 10^{-5} \text{ W}^{-1}$.

The solution of Eq. (2) can also be used to determine the optimum value for R , for given values of γ and V_0 . In Fig. 2(c), P_{SH} is plotted as a function of R for several powers ranging from $P_{ic} = 1.2$ to 1.8 W, using the fit results for γ and V_0 . The optimum for P_{SH} is seen to shift to smaller values of R for increasing P_{ic} , as the round-trip losses include the loss due to second-harmonic conversion.

In Fig. 2(b) the net conversion efficiency P_{SH}/P_{ic} is plotted as a function of P_{ic} . As can be seen in the graph, a

maximum net conversion efficiency of 75% is obtained, with 83% of the incident fundamental power (1.9 W) coupled into the cavity. Best performance was achieved with $P_{\text{in}} = 2.00(6)$ W resulting in 1.00(3) W of 389 nm coupled out of the cavity, which corresponds to $P_{\text{SH}} = 1.27(4)$ W of generated 389 nm light inside the crystal. The obtained second-harmonic conversion efficiency and SHG output power compare very well with the best results ever achieved using a setup of a similar design.^{4,14}

IV. ABSOLUTE FREQUENCY STABILIZATION

Distinct Lamb dips were produced using saturation parameters (defined as the intensity divided by the saturation intensity) for the pump beam ranging from 4 with a S/N ratio of 5, to 200 resulting in a S/N ratio of 25. The linewidth at the Lamb dip was measured to be 15–25 MHz, depending on the saturation parameter. This exceeds the natural linewidth by far, which we attribute to the combined effects of small misalignments, power broadening and pressure broadening.

The 389 nm laser is frequency stabilized to the transition within a few MHz, which is limited by the bandwidth of the Ti:S laser and the performance of the servo loop for frequency stabilization. The laser remains stabilized to the transition for hours.

By virtue of the large time constant of the servo loop, it is possible to temporarily shift the frequency of the 389 nm light by many MHz on a time scale of several milliseconds. This is done by adding a linear ramp to the frequency-control input of the Ti:S laser, which is too fast for the integrator in the servo loop to compensate. Such a change of laser frequency would, for instance, be ideally suited to further com-

press a 389 nm MOT.⁶ In a second application we switched off the second harmonic power considerably faster than can be achieved using mechanical shutters. When the cavity length is locked, suddenly applying a ramp on the high voltage controlling the PZT of *M4* brings the cavity out of resonance within 25 μs . The short switching time obtained with this inexpensive method was crucial for achieving low temperatures using a 389 nm optical molasses pulse applied to a cold cloud of He* atoms.^{6,8}

- ¹A. Robert, O. Sirjean, A. Browaeys, J. Poupard, S. Nowak, D. Boiron, C. I. Westbrook, and A. Aspect, *Science* **292**, 461 (2001).
- ²F. Pereira Dos Santos, J. Léonard, J. Wang, C. J. Barrelet, F. Perales, E. Rasel, C. S. Unnikrishnan, M. Leduc, and C. Cohen-Tannoudji, *Phys. Rev. Lett.* **86**, 3459 (2001).
- ³N. Herschbach, P. J. J. Tol, W. Vassen, W. Hogervorst, G. Woestenenk, J. W. Thomsen, P. van der Straten, and A. Niehaus, *Phys. Rev. Lett.* **84**, 1874 (2000).
- ⁴E. Jurdik, J. Hohlfeld, A. F. van Etteger, A. J. Toonen, W. L. Meerts, H. van Kempen, and Th. Rasing, *J. Opt. Soc. Am. B* **19**, 1660 (2002).
- ⁵T. Freegarde, and C. Zimmermann, *Opt. Commun.* **199**, 435 (2001).
- ⁶J. C. J. Koelemeij, A. S. Tychkov, T. Jeltse, W. Hogervorst, and W. Vassen, *J. Phys. B* **37**, 3501 (2004).
- ⁷T. W. Hänsch and B. Couillaud, *Opt. Commun.* **35**, 441 (1980).
- ⁸J. C. J. Koelemeij, thesis, Vrije Universiteit Amsterdam, 2004 (unpublished).
- ⁹G. D. Boyd and D. A. Kleinman, *J. Appl. Phys.* **39**, 3597 (1968).
- ¹⁰S. Bourzeix, M. D. Plimmer, F. Nez, L. Julien, and F. Biraben, *Opt. Commun.* **99**, 89 (1993).
- ¹¹M. Brieger, H. Büsener, A. Hese, F. v. Moers, and A. Renn, *Opt. Commun.* **38**, 423 (1981).
- ¹²E. S. Polzik and H. J. Kimble, *Opt. Lett.* **16**, 1400 (1991).
- ¹³A. Ashkin, G. D. Boyd, and J. M. Dziedzic, *IEEE J. Quantum Electron.* **QE-2**, 109 (1966).
- ¹⁴J. Mes, E. J. van Duijn, R. Zinkstok, S. Witte, and W. Hogervorst, *Appl. Phys. Lett.* **82**, 4423 (2003).